

ω - and ϕ -meson production in $pn \rightarrow dM$ reactions near threshold and OZI-rule violation

V.Yu. Grishina ^{a,1}, L.A. Kondratyuk ^{b,1} and M. Büscher ^{c,1}

^a*Institute for Nuclear Research, 60th October Anniversary Prospect 7A, 117312 Moscow, Russia*

^b*Institute of Theoretical and Experimental Physics, B. Cheremushkinskaya 25, 117259 Moscow, Russia*

^c*Forschungszentrum Jülich, Institut für Kernphysik, 52425 Jülich, Germany*

Abstract

We investigate the reactions $pn \rightarrow d\omega$ and $pn \rightarrow d\phi$ close to the corresponding thresholds. The S -wave amplitudes are calculated within the framework of the two-step model which is described by a triangle graph with π , ρ and ω mesons in the intermediate state. The cross sections of the reactions $pn \rightarrow d\omega$ and $pn \rightarrow d\phi$ are predicted to be significantly larger than the cross sections of the corresponding reactions $pp \rightarrow pp\omega$ and $pp \rightarrow pp\phi$ at the same values of the c.m. excess energy Q . The ratio of the yields of ϕ to ω is found to be $(30 \pm 7) \times 10^{-3}$.

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1 Introduction

It is well known (see e.g. [1–3]) that the ratio of the ϕ/ω yields

$$R = \frac{\sigma_{A+B \rightarrow \phi X}}{\sigma_{A+B \rightarrow \omega X}}, \quad (1)$$

is a particularly sensitive probe of the OZI rule [4]. Using the standard value for the deviation $\delta = \theta - \theta_i = 3.7^\circ$ from the ideal $SU(3)_f$ mixing angle $\theta_i =$

¹ Supported by DFG and RFFI.

35.3° we have $R/f = 4.2 \times 10^{-3}$ [3], where f is the ratio of the phase-space factors. However, experimental data show an apparent excess of R/f above the standard value which varies from $(10 - 30) \times 10^{-3}$ in πN and NN collisions to $(100 - 250) \times 10^{-3}$ in $\bar{N}N$ annihilation at rest and in flight (see e.g. the discussion in [3]). In Ref.[3] the large excess of R in pp and $\bar{p}p$ collisions over the prediction by the OZI rule was treated in terms of “shake-out” and “rearrangement” of an intrinsic $\bar{s}s$ component in the nucleon wave function. On the other hand, in papers [5,6] the strong violation of the OZI rule in $\bar{p}p$ annihilation at rest was explained in terms of hadronic intermediate $K\bar{K}^*$ states which might create ϕ mesons.

Another argument in favor of a large admixture of hidden strangeness in nucleons was related to an apparently large contribution of the ϕ -meson into the isoscalar spectral function which through the dispersion relation defines the isoscalar nucleon form factor (see Ref.[7]). However, as it was shown later (see [8] and references therein), the main contribution to the isoscalar spectral function near 1 GeV stems from correlated $\pi\rho$ exchange which does not involve strange quarks.

Therefore, the question whether there is a large admixture of hidden strangeness in nucleons seems to be unclarified. Thus, it is important to investigate such reactions where uncertainties in the interpretation of ω and ϕ production in terms of intermediate hadronic states are comparably small. In this paper we argue that a good choice in this respect is the reaction

$$pn \rightarrow dM . \quad (2)$$

Here and below M denotes the vector mesons ω and ϕ .

We analyze contributions of hadronic intermediate states into the S -wave amplitudes of the reactions $pn \rightarrow d\phi$ and $pn \rightarrow d\omega$ within the framework of the two-step model (TSM) described by triangle graphs with π -, ρ - and ω -meson exchanges. Previously this model was applied to the description of the Pontecorvo reactions $\bar{p}d \rightarrow pM$ (see, e.g., Ref.[9,10]). In a recent paper (see Ref.[11]) it was demonstrated that the TSM can also describe the cross section of the reaction $pn \rightarrow d\eta$ near threshold with a reasonable choice of the coupling constants and cut-off parameters for π -, ρ - and ω -meson exchanges. To predict the cross sections of the reactions $pn \rightarrow d\omega$ and $pn \rightarrow d\phi$ we use a similar approach and the same set of parameters for the MNN coupling constants and cut-off parameters. Note that if the ϕ and ω yields will be measured in reaction (2) near threshold (which e.g. can be done at COSY-Jülich), the results can be useful for a better understanding of the OZI-rule violation dynamics. For example, any significant deviation from the prediction of the two-step model could be an evidence for the above mentioned “shake out” or “rearrangement” of an intrinsic $\bar{s}s$ component in the nucleon wave function.

Note that recent measurements of the ϕ/ω ratio in the reaction $pd \rightarrow {}^3HeX$ (performed at SATURNE II [12,13]) yield

$$R/f = (63 \pm 5 {}^{+27}_{-8}) \times 10^{-3} \quad (3)$$

which is also clearly above the expectation 4.2×10^{-3} . However the dynamics of the reaction $pd \rightarrow {}^3HeX$ is yet not well understood. According to [14] the two-step model underestimates the SATURNE data by a factor 2, while according to [15] the discrepancy of the two-step model with the data might be even larger when spin-effects are taken into account.

Experiments on ω and ϕ production in the reaction $pp \rightarrow ppM$ close to threshold were performed by the SPES3 and DISTO collaborations at SATURNE [16,17] (see also the calculations of ω production in [18]). According to the DISTO data the ratio of the ϕ/ω production cross sections at 2.85 GeV is $\sigma_{\text{tot}}(pp \rightarrow pp\phi)/\sigma_{\text{tot}}(pp \rightarrow pp\omega) = (3.7 \pm 1.3) \times 10^{-3}$. Introducing corrections for phase-space effects the authors of Ref.[16] found that in this case the ϕ/ω ratio is $(49 \pm 26) \times 10^{-3}$. Note that near threshold the dynamics of the reactions $pp \rightarrow ppM$, $pn \rightarrow pnM$ and $pn \rightarrow dM$ are different because the first one is constrained by the Pauli principle and the two protons in the final state should be in a 1S_0 state. In the third case the final pn system is in the 3S_1 state while in the second case it can be in both states. Therefore, a possible violation of the OZI rule is expected to be different in all those cases.

Finally, another interesting point is that within the framework of the line-reverse invariance (LRI) assumption the reaction $pn \rightarrow dM$ can be related to the Pontecorvo reaction $\bar{p}d \rightarrow MN$. The data from the OBELIX and Crystal-Barrel collaborations result in a ϕ/ω ratio of about $(230 \pm 60) \times 10^{-3}$ [19,20]. Therefore, if LRI is applicable we expect the violation of the OZI rule in the reaction $pn \rightarrow dM$ to be much larger than it is predicted by the two-step model, which assumes the dominance of the hadronic intermediate states.

The paper is organized as follows. In Sect. 2 we derive the amplitudes of the reactions $pn \rightarrow d\phi$ and $pn \rightarrow d\omega$ near threshold within the framework of the two-step model. In Sect. 3 we discuss the choice of parameters and present the results of calculations. Sect. 4 contains our conclusions.

2 The non-relativistic two-step model for the reaction $pn \rightarrow dM$

The triangle diagrams describing the TSM are shown in Fig. 1. Besides the π exchange we also take into account ρ and ω exchanges.

In the beginning let us consider the π^0 -exchange term. In order to preserve the

correct structure of the amplitude under permutations of the initial nucleons (which should be symmetric in the isoscalar state) the amplitude is written as the sum of the t - and u -channel contributions in the following form

$$T_{pn \rightarrow dM}^\pi(s, t, u) = A_{pn \rightarrow dM}^\pi(s, t) + A_{pn \rightarrow dM}^\pi(s, u) , \quad (4)$$

where M is the vector meson ω or ϕ . $s = (p_1 + p_2)^2$, $t = (p_3 - p_1)^2$, and $u = (p_3 - p_2)^2$ where p_1 , p_2 , p_3 , and p_4 are the 4-momenta of the proton, neutron, meson M and deuteron, respectively. Since we are interested in the calculation of the cross section of reaction (2) near threshold where the momenta of the deuteron and the meson are comparatively small, we can use a non-relativistic description of those particles by neglecting the 4th components of their polarization vectors. The relative motion of nucleons inside the deuteron is also treated non-relativistically. Then one can write the two terms on the right hand side of Eq. (4) as follows (see also [11])

$$A_{pn \rightarrow dM}^\pi(s, t) = \frac{f_\pi}{m_\pi} \varphi_{\lambda_2}^T(\vec{p}_2) (-i\sigma_2) \vec{\sigma} \cdot \vec{M}^\pi(\vec{p}_1) \vec{\sigma} \cdot \vec{\epsilon}_d^* \vec{\sigma} \cdot \vec{\epsilon}_M^* \varphi_{\lambda_1}(\vec{p}_1) \times A_{\pi^0 N \rightarrow MN}(s_1, t) , \quad (5)$$

$$A_{pn \rightarrow dM}^\pi(s, u) = \frac{f_\pi}{m_\pi} \varphi_{\lambda_1}^T(\vec{p}_1) (-i\sigma_2) \vec{\sigma} \cdot \vec{M}^\pi(-\vec{p}_1) \vec{\sigma} \cdot \vec{\epsilon}_d^* \vec{\sigma} \cdot \vec{\epsilon}_M^* \varphi_{\lambda_2}(\vec{p}_2) \times A_{\pi^0 N \rightarrow MN}(s_1, u) , \quad (6)$$

where $\vec{\epsilon}_d$ and $\vec{\epsilon}_M$ are the polarization vectors of the deuteron and the meson; φ_λ are the spinors of the nucleons in the initial state, m_π and f_π are the pion mass and πNN coupling constant. The vector function $\vec{M}^\pi(\vec{p}_1)$ is defined by the integral

$$\vec{M}^\pi(\vec{p}_1) = \sqrt{2m} \int (\vec{k} + \vec{p}_1) \Phi_\pi(\vec{k}, \vec{p}_1) \Psi_d(\vec{k}) \frac{d^3k}{(2\pi)^{3/2}} , \quad (7)$$

$$\Phi_\pi(\vec{k}, \vec{p}_1) = \frac{F_\pi(q^2)}{q^2 - m_\pi^2} , \quad (8)$$

which contains the deuteron wave function $\Psi_d(\vec{k})$ and the form factor at the πNN vertex $F_\pi(q^2)$. Other kinematical quantities which are also dependent on the momenta \vec{p}_1 and \vec{k} are defined as follows

$$\begin{aligned} q^2 &= m_\pi^2 - \delta_0(\vec{k}^2 + \beta(\vec{p}_1)) - 2\vec{p}_1 \vec{k}, \quad \vec{q} = \vec{k} + \vec{p}_1 , \\ \beta(\vec{p}_1) &= (\vec{p}_1^2 + m_\pi^2 - T_1^2)/\delta_0 , \quad \delta_0 = 1 + T_1/m, \quad T_1 = \sqrt{\vec{p}_1^2 + m^2} - m . \end{aligned}$$

with m being the nucleon mass.

Near threshold we take into account only the S -wave part of the amplitude of the elementary reaction $\pi N \rightarrow MN$. Deriving Eqs.(5,6) we use the following spin structure of the $\pi^0 N \rightarrow MN$ amplitude

$$\langle p'_3 \lambda'_3; p'_4 \lambda'_4 | \hat{T}_{\pi N \rightarrow NM} | p'_1; p'_2 \lambda'_2 \rangle = \varphi_{\lambda'_4}^*(\vec{p}'_4) \bar{\epsilon}_{\lambda'_3}^{*(M)} \cdot \vec{\sigma} \varphi_{\lambda'_2}^*(\vec{p}'_2) A_{\pi N \rightarrow NM}(s_1, t_1), \quad (9)$$

where p'_1, p'_2, p'_3 and p'_4 are the 4-momenta of the π meson, the initial nucleon, the final nucleon and the vector meson, respectively. The λ'_i are the spin projections of the particles, $\bar{\epsilon}^{(V)}$ is the polarization vector of the vector meson and $s_1 = (p'_1 + p'_2)^2 = (p'_3 + p'_4)^2$, $t_1 = (p'_1 - p'_4)^2 = (p'_2 - p'_3)^2$.

The invariant amplitude is normalized to the total cross section as follows

$$|A_{\pi^0 N \rightarrow MN}(s_1, t)|^2 = |A_{\pi^0 N \rightarrow MN}(s_1, u)|^2 = \frac{8}{3} \pi s_1 \frac{p_\pi^{\text{cm}}}{p_M^{\text{cm}}} \sigma_{\pi^- p \rightarrow Mn} \quad (10)$$

where s_1 is the invariant mass squared of the Mn system.

It was shown in Ref.[11] that apart from the π -exchange contributions heavier vector-meson exchanges — especially of ρ mesons — are important for the case of the reactions $pn \rightarrow d\eta$ and $pn \rightarrow d\eta'$. In our case the amplitudes for the vector-meson exchanges can be written in the form

$$A_{pn \rightarrow dM}^V(s, t) = \frac{G_V}{2m} \varphi_{\lambda_2}^T(\vec{p}_2) (-i \sigma_2) \cdot A_{V^0 N \rightarrow MN}(s_1, t) \times \left\{ \vec{M}_1^V(\vec{p}_1) \cdot \bar{\epsilon}_M^* \vec{\sigma} \cdot \bar{\epsilon}_d^* + \vec{M}_2^V(\vec{p}_1) \cdot \bar{\epsilon}_d^* \vec{\sigma} \cdot \bar{\epsilon}_M^* - \vec{\sigma} \cdot \vec{M}_2^V(\vec{p}_1) \bar{\epsilon}_d^* \cdot \bar{\epsilon}_M^* + i [\vec{M}_2^V(\vec{p}_1) \times \bar{\epsilon}_d^*] \cdot \bar{\epsilon}_M^* \right\} \varphi_{\lambda_1}(\vec{p}_1) \quad (11)$$

$$A_{pn \rightarrow dM}^V(s, u) = \frac{G_V}{2m} \varphi_{\lambda_1}^T(\vec{p}_1) (-i \sigma_2) \cdot A_{V^0 N \rightarrow MN}(s_1, u) \times \left\{ \vec{M}_1^V(-\vec{p}_1) \cdot \bar{\epsilon}_M^* \vec{\sigma} \cdot \bar{\epsilon}_d^* + \vec{M}_2^V(-\vec{p}_1) \cdot \bar{\epsilon}_d^* \vec{\sigma} \cdot \bar{\epsilon}_M^* - \vec{\sigma} \cdot \vec{M}_2^V(-\vec{p}_1) \bar{\epsilon}_d^* \cdot \bar{\epsilon}_M^* + i [\vec{M}_2^V(-\vec{p}_1) \times \bar{\epsilon}_d^*] \cdot \bar{\epsilon}_M^* \right\} \varphi_{\lambda_1}(\vec{p}_1) \quad (12)$$

where

$$\vec{M}_1^V(\vec{p}_1) = \sqrt{2m} \int [(\vec{k} - \vec{p}_1) + \frac{\vec{k}^2 - \vec{p}_1^2}{m_V^2} (\vec{k} + \vec{p}_1)] \Phi_V(\vec{k}, \vec{p}_1) \Psi_d^*(\vec{k}) \frac{d^3 k}{(2\pi)^{3/2}} \quad (13)$$

and

$$\vec{M}_2^V(\vec{p}_1) = \sqrt{2m} \int (1 + \kappa_V)(\vec{k} + \vec{p}_1) \Phi_V(\vec{k}, \vec{p}_1) \Psi_d^*(\vec{k}) \frac{d^3 k}{(2\pi)^{3/2}} . \quad (14)$$

The function $\Phi_V(\vec{k}, \vec{p}_1)$ describes the product of the V -meson propagator $(q^2 - M_V^2)^{-1}$ and the form factor at the VNN vertex $F_V(q^2)$. It is defined by Eq. (8) where m_π^2 should be substituted by m_V^2 . G_V and $\kappa_V G_V$ are the vector and tensor coupling constants respectively.

The general spin structure of the $VN \rightarrow MN$ amplitude near threshold has the following form

$$\begin{aligned} \langle p'_3 \lambda'_3; p'_4 \lambda'_4 | \hat{T}_{VN \rightarrow NM} | p'_1 \lambda'_1; p'_2 \lambda'_2 \rangle = \\ \varphi_{\lambda'_4}^*(\vec{p}'_4) \left(\vec{\epsilon}_{\lambda'_3}^{*(M)} \cdot \vec{\epsilon}_{\lambda'_1}^{(V)} A_{VN \rightarrow NM}(s_1, t_1) + \right. \\ \left. i \left[\vec{\epsilon}_{\lambda'_3}^{*(M)} \times \vec{\epsilon}_{\lambda'_1}^{(V)} \right] \cdot \vec{\sigma} B_{VN \rightarrow NM}(s_1, t_1) \right) \varphi_{\lambda'_2}^*(\vec{p}'_2) , \end{aligned} \quad (15)$$

where the notations are similar to the ones in Eq.(9). Two invariant amplitudes $A_{VN \rightarrow NM}(s_1, t_1)$ and $B_{VN \rightarrow NM}(s_1, t_1)$ are necessary to describe two possible transitions $(\frac{1}{2})^- \rightarrow (\frac{1}{2})^-$ and $(\frac{3}{2})^- \rightarrow (\frac{3}{2})^-$. It is known from the data on Compton scattering (see, e.g., [28]) that the spin-flip amplitude $B_{\gamma N \rightarrow \gamma N}(s_1, t_1)$ is small as compared with the non spin-flip amplitude $A_{\gamma N \rightarrow \gamma N}(s_1, t_1)$ except in the Δ -resonance region (see, e.g., [28]). Following the arguments of the Vector-Dominance Model (VDM) we assume that this amplitude is also small in our case and take into account only the first non spin-flip term in Eq.(15).

Note that the amplitudes A^π and A^ρ correspond to the exchange of neutral π and ρ mesons only (see the left diagrams in Fig. 1). To take into account also the charged π and ρ exchanges we have to multiply amplitude (4) by a factor 3. Of course in the case of ω exchange such a factor is not necessary.

Therefore, the differential cross section of reaction (2) can be written as

$$\begin{aligned} \frac{d\sigma_{pn \rightarrow dM}}{dt} = \\ \frac{1}{64\pi s} \frac{1}{(p_1^{\text{cm}})^2} F(I) \overline{|A_{pn \rightarrow dM}(s, t) + A_{pn \rightarrow dM}(s, u)|^2} . \end{aligned} \quad (16)$$

where the isospin factor $F(I)$ is equal to 9 for isovector exchanges (ρ and π) and 1 for isoscalar exchange (ω).

3 Choice of parameters and results of calculations

We assume the form factors $F_\pi(q^2)$ and $F_V(q^2)$ to be of monopole type. Recent QCD lattice calculations [21] suggest that the cut-off in the pion form factor should be quite soft $\Lambda_\pi \simeq 0.8$ GeV/c (see also Refs. [22,23]). Of course such a soft pion form factor suppresses pion exchange and contributions of heavier meson exchanges become more important. This for example was demonstrated in Ref. [11] where it was found that the ρ -exchange contribution in the reactions $pn \rightarrow d\eta$ and $pn \rightarrow d\eta'$ is significant. Here also $\Lambda_\pi = 0.8$ GeV/c is used.

The coupling constants and vertex form factors for ρ and ω mesons are taken from the full Bonn NN potential [24]: $G_\rho^2/4\pi = 0.84$, $\kappa_\rho = 6.1$, $G_\omega^2/4\pi = 20$, $\kappa_\omega = 0$ and $\Lambda_\rho = 1.4$ GeV/c, $\Lambda_\omega = 1.5$ GeV/c.

For the deuteron wave function we take the parameterization from Ref.[25] and neglect the D -wave part. As it was demonstrated in Ref.[10] for the case of the reaction $\bar{p}d \rightarrow Mn$ (where the same structure integrals (7) for π , ρ and ω exchanges occur) the D -wave term of the deuteron wave function gives a negligibly small contribution compared to the S -wave term.

To define the amplitudes $\pi N \rightarrow MN$ we use the following values of the S -wave cross sections (taken from Ref.[26]):

$\sigma_{\pi^-p \rightarrow \omega n} = (8.3 \pm 0.07)p_{\text{cm}}^M \mu\text{b}$ and $\sigma_{\pi^-p \rightarrow \phi n} = (0.29 \pm 0.06)p_{\text{cm}}^M \mu\text{b}$ (p_{cm}^M in MeV/c). The experimental data show that the angular distribution in the reaction $\pi^-p \rightarrow n\omega$ is isotropic and the S -wave is dominant at least up to $k_V^{\text{cm}}(s_1) = 260$ MeV/c (see the comment on p.2805 in [26]). We ignore an apparent suppression of the S -wave amplitude very close to threshold ($k_V^{\text{cm}}(s_1) \leq 80-100$ MeV/c), reported in Ref.[26], because according to Ref.[27] this effect has a kinematical origin.

The contributions from the ρ and ω exchanges are calculated using the vector-dominance model (VDM) prediction for the amplitude $\rho N \rightarrow \omega(\phi)N$ and assuming that for non-diagonal cases $A_{\omega N \rightarrow MN} \approx A_{\rho^0 N \rightarrow MN}$. We derive the S -wave $\gamma N \rightarrow \omega N$ amplitude from the ABBHHM data at $E_\gamma = 1.3$ GeV (see Ref.[28]) using a value of the cross section of the reaction $\gamma p \rightarrow \omega p$ equal to 5.6 – 7.8 μb . This would give the $\rho p \rightarrow \omega p$ cross section of about 2.7 ± 0.5 mb at low energies. The ratio of the $\gamma p \rightarrow \phi p$ and $\gamma p \rightarrow \omega p$ amplitudes squared was found from the data at $s = 5 - 6$ GeV² to be 0.06 – 0.07. Then we assumed that it is the same for the the case of the reactions $\rho p \rightarrow \phi p$ and $\rho p \rightarrow \omega p$. For the elastic ωN scattering cross section at low energies we took the value 15 mb which was evaluated in Ref.[29] within the sigma-exchange model and is in agreement with previous estimations made using the Quark Model.

Since the relative phases of the different contributions are not known we cal-

culate the cross section of the reaction $pn \rightarrow dM$ as the incoherent sum

$$\sigma_{pn \rightarrow dM} = N[\sigma^{(\pi)} + \sigma^{(\rho)} + \sigma^{(\omega)}] . \quad (17)$$

In Fig.2 taken from Ref.[11] we show how the TSM (with the same coupling constants and cut-off parameters for π , ρ and ω exchanges and the S -wave amplitudes $Vp \rightarrow \eta p$ and $Vp \rightarrow \eta' p$ estimated using VDM from the photo-production data) describes the experimental data on the reaction $pn \rightarrow d\eta$. The cross section of the reaction $pn \rightarrow d\eta$ is presented as a function of the c.m. excess energy Q . The dashed curve shows the π -exchange contribution alone whereas the dash-dotted curve describes the sum of π , ρ , and ω exchanges. The solid curve includes all contributions (π , ρ , ω) multiplied with a normalization factor $N = 0.68$ in order to take into account effects from the initial state interaction (ISI). The data points for are taken from Refs.[30] (open circles) and [31] (filled circles). The reduction factor appeared to be not very different from the prediction of the ISI effect within a simple model which assumes the dominant contribution from the on-shell rescattering [32] and gives $\lambda_{\text{ISI}} \simeq 0.5$.

As we see from Fig.2 pion exchange calculated with the soft cut-off parameter cannot describe the η -production data and the contribution from heavier meson exchanges (and especially of ρ [11]) is quite important.

In Figs.3 and 4 we present the predictions of the TSM for the cross sections of the ω and ϕ production. The contribution of pion exchange is shown by the dashed curves. The lower and upper curves show the minimal and maximal values of the π -exchange contribution demonstrate which follow from the experimental errors of the elementary cross sections. The dash-dotted curves describe the sum of π -, ρ - and ω -exchange contributions. The solid curves represent the results including all contributions (π , ρ , ω) multiplied with the same normalization factor $N = 0.68$ as in the case of η - production in order to take into account effects from ISI. It is clearly seen that similar to the case of η production the ρ -exchange contribution to the cross sections of the reactions is very significant. The relative contribution of π exchange is about 20 % in the case of ω production and is almost 2 times less in the case of ϕ production. The ω exchange is more important in the case of ω production where it gives about 20%; in the case of ϕ production its relative contribution is about 5%.

The cross sections of the reactions $pn \rightarrow \omega d$ and $pn \rightarrow \phi d$ can be parameterized as follows

$$\sigma_{pn \rightarrow dM} \approx D_M \sqrt{Q} , \quad (18)$$

where $D_\omega = (2.7 \pm 0.3) \mu\text{b}/\text{MeV}^{1/2}$ and $D_\phi = (0.09 \pm 0.02) \mu\text{b}/\text{MeV}^{1/2}$. At very low Q which are of the order of the resonance width each cross section

might be a little larger because of the finite widths of the ω and ϕ [16].

In Fig.3 we show also experimental data on the near-threshold production of ω mesons in the $pp \rightarrow pp\omega$ reaction [16]. Near threshold the predicted cross section of ω production with the deuteron in the final state is much higher than that of the reaction the $pp \rightarrow pp\omega$. This is very similar to the case of η production (see , e.g., [30,31]) and is related to isospin and phase-space factors (see, e.g., [33]).

Let us discuss the relation between $\sigma(pp \rightarrow pp\omega)$ and $\sigma(pn \rightarrow d\omega)$ near threshold in more detail. Fälldt and Wilkin [34] proposed the following parameterization of the cross section of the reaction $pp \rightarrow ppM$ near the threshold

$$\sigma_{pp \rightarrow ppM} = C_M \left(\frac{Q}{\epsilon} \right)^2 \left(1 + \sqrt{1 + Q/\epsilon} \right)^{-2}. \quad (19)$$

This formula takes into account the strong final state interaction of two protons including also Coulomb distortion with $\epsilon \approx 0.45$ MeV. For η and ω production we have $C_\eta = (110 \pm 20)$ nb and $C_\omega = (37 \pm 8)$ nb [16]. At $Q=15$ MeV we have $\sigma(pp \rightarrow pp\eta) \approx 2.6 \mu\text{b}$ ($\sigma(pp \rightarrow pp\omega) \approx 1 \mu\text{b}$) which is 15(10) times less than the cross section of the reaction $pn \rightarrow d\eta$ ($pn \rightarrow d\omega$). Note that in line with suggestions by Wilkin (see, e.g., [33]) the ratios $\sigma(pn \rightarrow d\eta)/\sigma(pp \rightarrow pp\eta)$ and $\sigma(pn \rightarrow d\omega)/\sigma(pp \rightarrow pp\omega)$ are, in fact, not very different.

The reaction $pp \rightarrow pp\omega$ near the threshold was also analyzed within the framework of the meson-exchange model in Ref.[18]. Adjusting the cut-off parameter of the form factor to the low energy data the authors of Ref.[18] calculated the cross section of the reaction $pp \rightarrow pp\omega$ for proton incident energies up to 2.2 GeV. This model predicts a cross section of about 15–20 μb at $Q \approx 100$ MeV which is still not very different from parameterization (19). If parameterizations (18) and (19) would be valid up to $Q = 1$ GeV then the cross section of the reaction $\sigma(pp \rightarrow pp\omega)$ would reach the same value as the cross section of the reaction $pn \rightarrow d\omega$ only at 900 MeV. Of course those formulas can not be valid up to such large values of Q . Estimations within the framework of the Quark-Gluon String Model shows that the cross section of the reaction $pn \rightarrow d\omega$ can reach maximum of about 30–50 μb at $Q = 100$ –200 MeV and then will start to fall (see [35]). According to the parameterization of Ref.[36] the cross section of the reaction $\sigma(pp \rightarrow pp\omega)$ reaches the value of 30 μb at $Q \approx 200$ MeV. Therefore we can expect that in a rather broad interval of Q (at least up to about 100–150 MeV) the cross section of the reaction $pn \rightarrow d\omega$ will be larger than the cross section of the reaction $\sigma(pp \rightarrow pp\omega)$. This gives quite a good chance that the reaction $pn \rightarrow d\omega$ can be detected using missing mass method at COSY by measuring the forward deuteron and spectator proton in the reaction $pd \rightarrow d\omega p_{\text{sp}}$.

For the case of ϕ production we also expect that near threshold the cross section of the reaction $pn \rightarrow d\phi$ will be larger than the cross section of the reaction $pp \rightarrow pp\phi$. The latter was estimated using DISTO data in Ref.[33] and found to be equal to $0.28 \pm 0.14 \mu\text{b}$ at $Q = 82 \text{ MeV}$. Though there are uncertainties in extrapolating the prediction of the TSM (Eq.(18)) to such large Q we would have $\sigma(pn \rightarrow d\phi) \approx 0.6 - 1 \mu\text{b}$ at this Q .

Let us discuss now the ϕ/ω ratio. TSM predicts the following value

$$R_{pn \rightarrow dM} = D_\phi/D_\omega = (30 \pm 7) \times 10^{-3}. \quad (20)$$

This is lower than the corresponding ratio in pp collisions [16]

$$R_{pp \rightarrow ppM} = C_\phi/C_\omega = (49 \pm 26) \times 10^{-3}. \quad (21)$$

and in the reaction $pd \rightarrow {}^3\text{He} M$ (see Eq.(3)). It is closer to the ratio of the ϕ to ω yields in $\pi^- p$ collisions (see, e.g., the discussion in Ref.[33])

$$R_{\pi^- p \rightarrow nM} = (37 \pm 8) \times 10^{-3}. \quad (22)$$

Another estimate of R can be found if we assume the line-reverse invariance of the amplitudes, which correspond to the diagrams presented in Fig.1. In this case we have

$$\begin{aligned} \overline{|T_{pn \rightarrow dM}^{\text{LRI}}(s, t)|^2} &= \overline{|A_{pn \rightarrow dM}^{\text{LRI}}(s, t) + A_{pn \rightarrow dM}^{\text{LRI}}(s, u)|^2} \\ &= \overline{|A_{\bar{p}d \rightarrow nM}(s, t) + A_{\bar{p}d \rightarrow nM}(s, u)|^2} \end{aligned} \quad (23)$$

and can define the ratio

$$R_{\text{LRI}} = |T_{pn \rightarrow d\phi}^{\text{LRI}}|^2 / |T_{pn \rightarrow d\omega}^{\text{LRI}}|^2 = |T_{\bar{p}d \rightarrow n\phi}|^2 / |T_{\bar{p}d \rightarrow n\omega}|^2. \quad (24)$$

Adopting the result of the OBELIX collaboration $Y(\bar{p}d \rightarrow n\phi)/Y(\bar{p}d \rightarrow n\omega) = (230 \pm 60) \times 10^{-3}$ we get

$$\begin{aligned} R_{\text{LRI}} &= |T_{\bar{p}d \rightarrow n\phi}|^2 / |T_{\bar{p}d \rightarrow n\omega}|^2 \\ &\approx (p_{\text{cm}}^\omega / p_{\text{cm}}^\phi) (Y(\bar{p}d \rightarrow n\phi)/Y(\bar{p}d \rightarrow n\omega)) \simeq (250 \pm 60) \times 10^{-3}, \end{aligned} \quad (25)$$

which is larger by an order of magnitude than the prediction of the TSM given by Eq.(20). If experimental studies will find an essential excess of $R(\phi/\omega)$ over the value predicted by the two-step model it might be interpreted as a possible contribution of the intrinsic $s\bar{s}$ component in the nucleon wave function.

4 Conclusions

Using the two-step model which is described by triangle graphs with π -, ρ - and ω -meson exchanges we calculated the cross sections of the reactions $pn \rightarrow dM$, where $M = \omega$ or ϕ , close to threshold. The predicted cross section of the reaction $pn \rightarrow d\omega$ is found to be significantly larger than the cross section of the reaction $pp \rightarrow pp\omega$. The same is expected to be the case for ϕ production. We find a ϕ/ω ratio of $R_{pn \rightarrow dM} = (30 \pm 7) \times 10^{-3}$. The measurement of the ϕ and ω yields in the reaction $pn \rightarrow dM$ at the same energy release Q will be useful for a better understanding of the mechanism of the OZI-rule violation.

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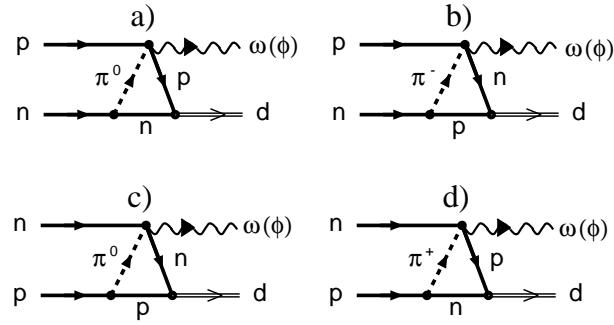


Fig. 1. Diagrams describing the two-step model (TSM). Note that besides the π -exchange contribution also diagrams involving the exchange of ρ and ω mesons are taken into account.

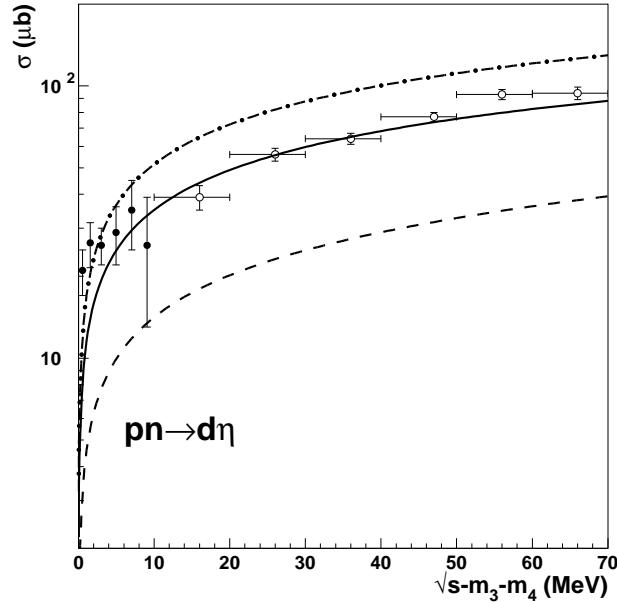


Fig. 2. Cross section of the reaction $pn \rightarrow d\eta$ as a function of the c.m. excess energy (taken from Ref.[11]). The dashed curve shows the π -exchange contribution whereas the dash-dotted curve is the sum of π , ρ , and ω exchanges. The solid curve includes all contributions (π , ρ , ω) multiplied with a normalization factor $N = 0.68$ in order to take into account effects from the initial state interaction (see text). The data points for are taken from Refs. [30] (open circles) and [31] (filled circles).

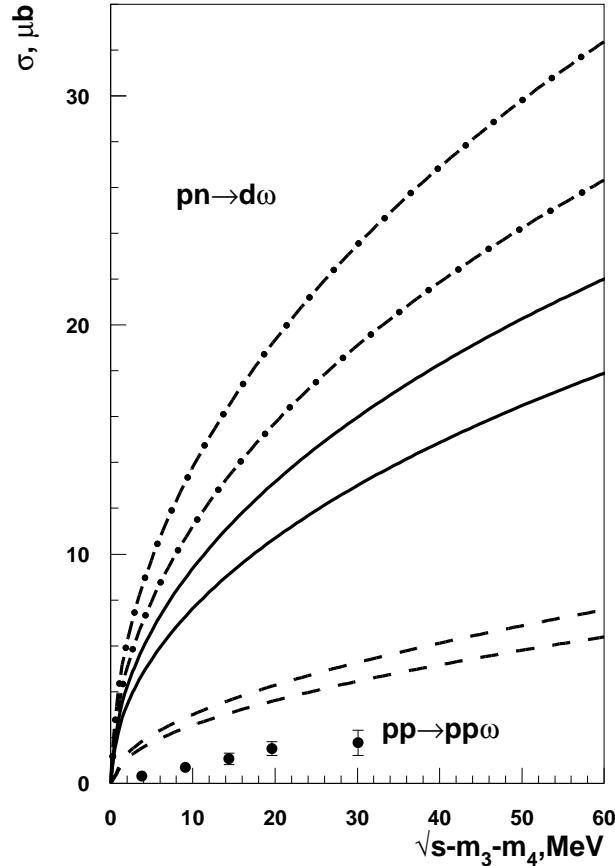


Fig. 3. Cross section of the reaction $pn \rightarrow d\omega$ as a function of the c.m. excess energy. The dashed curves show the π -exchange contribution alone whereas the dash-dotted curves are the sums of π , ρ , and ω exchanges. The solid curves include all contributions (π , ρ , ω) multiplied with a normalization factor $N = 0.68$ in order to take into account effects from the initial state interaction (see text). The upper and lower dashed, solid and dash-dotted curves are the results obtained using the maximal and minimal values of the elementary $\pi N \rightarrow \omega N$ and $V N \rightarrow \omega N$ S -wave amplitudes (see text). The data points are the data on the reaction $pp \rightarrow pp\omega$ from Ref.[16].

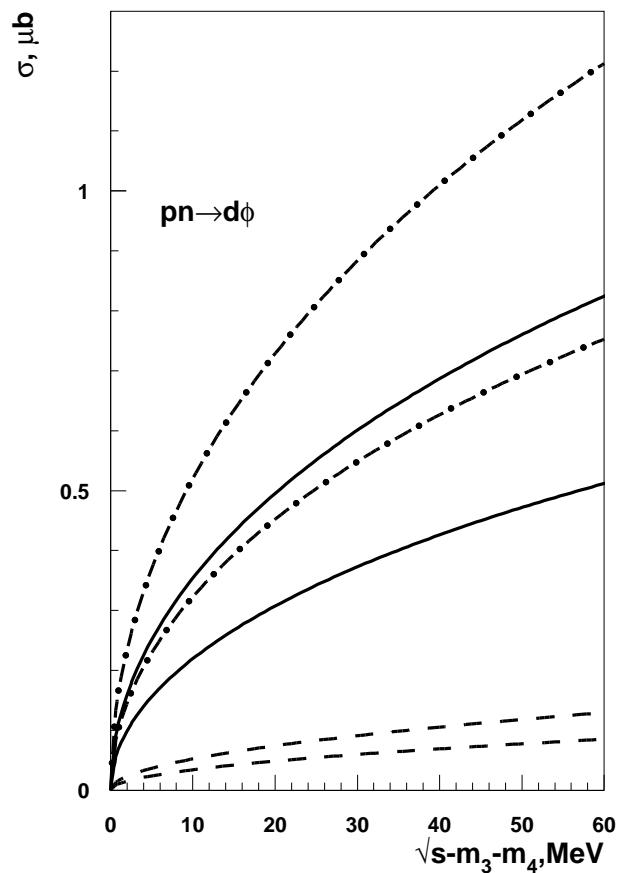


Fig. 4. Cross section of the reaction $pn \rightarrow d\phi$ as a function of the c.m. excess energy. The meaning of the curves is the same as in Fig.3.